Plasma Physics Studies in Cylindrical Hall Thrusters

Experimental Project

Erik Granstedt

Hall Thruster eXperiment
Princeton Plasma Physics Laboratory

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Outline

1. Motivation
   - Introduction
   - Current HT research
2. Non-self-sustained regime
   - Performance Enhancement
   - Ion Energy
3. Filament Experiments
   - Experiment set-up
   - Filament-cathode Measurement Results

Why we do what we do

Space: the final frontier
...to boldly go where no man has gone before

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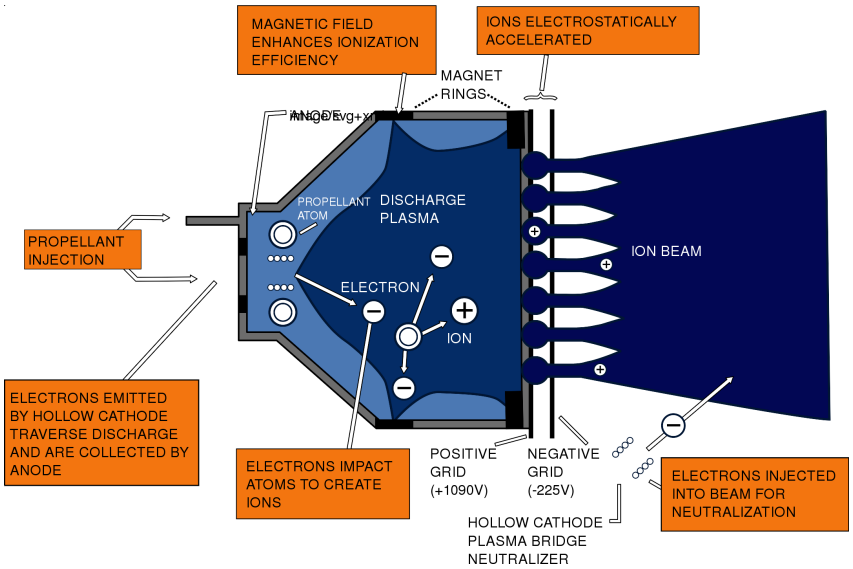
Why use plasmas for space propulsion?

- Momentum conservation gives the rocket equation:
  - $\frac{\partial(mv)}{\partial t} = 0 \quad m\frac{\partial v}{\partial t} = -v_{ex}\frac{\partial m}{\partial t}$
  - $\Delta v = v_{ex} ln \frac{m_0+m_p}{m_0}$
- for a given Δv, v_{ex} determines m_p: necessary propellant mass
- rockets use chemical reactions to heat the propellant; v_{ex} limited to chemical energies (typ $\sim$ 4 km/s)
- electric thrusters accelerate the propellant with electric fields, drawing power from a power supply
  - $P = v_{ex}T$, so thrust is limited by power supply; must operate for thousands of hours
  - Electrostatic thrusters $v_{ex} \sim$ 100 km/s, Hall thruster $v_{ex} \sim$ 16 km/s
  - accelerator ($P \sim$ 2kW, $v \sim c$, $T \sim 1\mu\mathrm{N}$)

Electrostatic Thrusters (Ion engine)

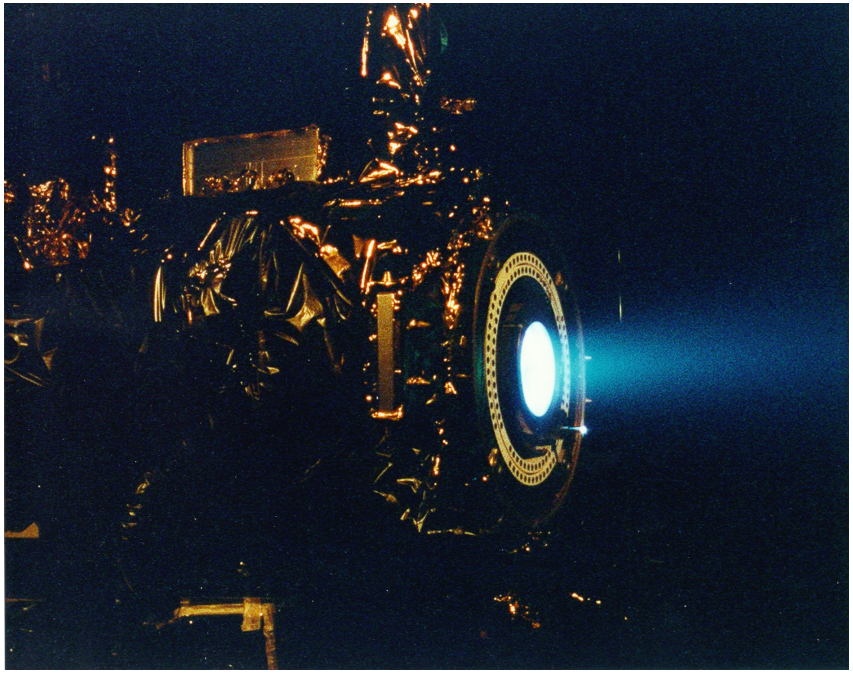


http://www.grc.nasa.gov/WWW/ion/overview/overview.htm

- NSTAR: 30cm diameter
- grids < 1mm thick, 0.7mm apart

- ions born via electron bombardment in region of high potential
- ions diffuse to grids
- ions extracted by sheath around first grid
- accelerated by potential difference between grids
- ion beam neutralized by electrons from hollow cathode

Electrostatic Thrusters in Operation



http://nmp.jpl.nasa.gov/ds1/

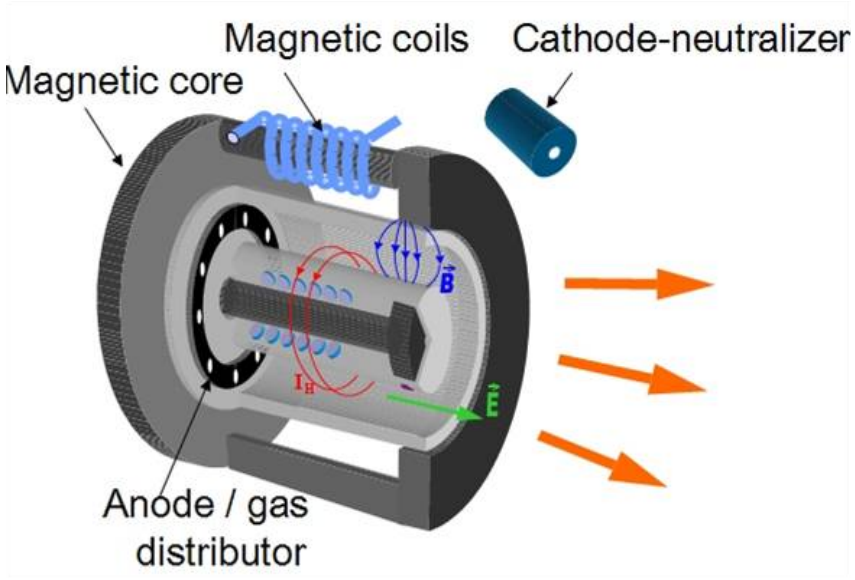
Performance:

- v_{ex}: 142 km/s
- thrust: 19–92mN
- power: 0.5–2.3kW
- divergence: 20°
- run time: $>$ 10000 hours
- efficiency: 65%

Issues:

- grid erosion
- hollow cathode lifetime
- low thrust density (space-charge limited)

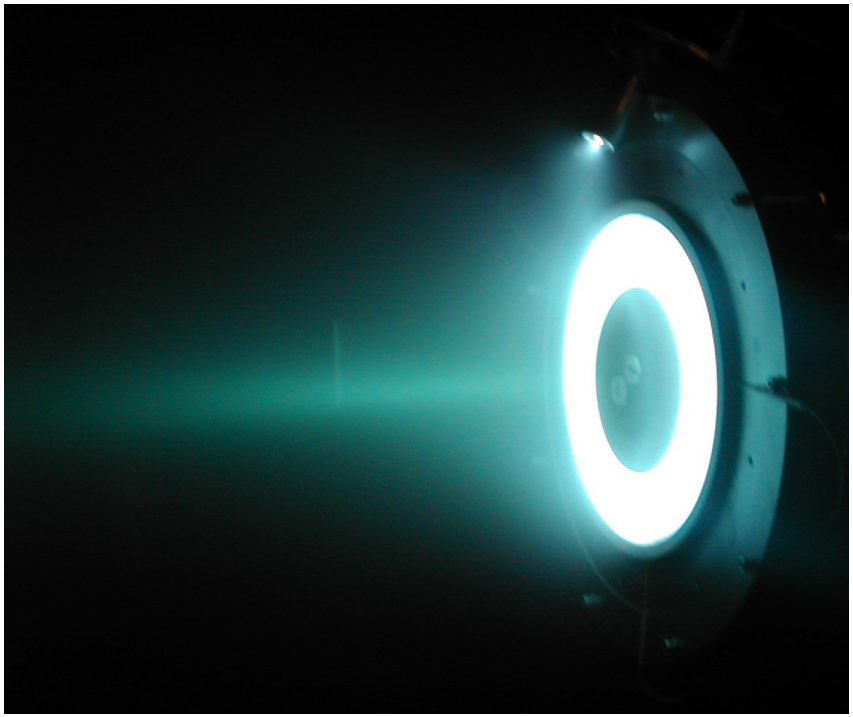
Hall Thrusters



- 2kW PPPL thruster: 9cm dia
- B$\sim$ 100G, $T_e \sim$ 10–60eV, $T_i \sim$ 1eV,$n_e \sim 10^{11}$ $10^{12}\mathrm{cm}^{-3}$
- $\lambda_e, \lambda_i >> L$, $\Omega_e/\nu_{ee} \sim 100$

- azimuthal electron orbits ($E \times B$ drift), diffuse toward anode
- electrons neutralize ion space charge
- $\rho_e << L << \rho_i$: electrostatic ion acceleration
- ion beam neutralized by electrons from hollow cathode

Hall Thrusters in Operation



2kW PPPL thruster

Performance:

- v_{ex}: 16–25 km/s
- thrust: 2–1000mN
- power: 0.2–50kW
- divergence: 50°
- efficiency: 50–60%

Applications:

- orbit station-keeping
- orbit insertion
- inner-planetary missions

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Hall thruster Issues & Basic Physics

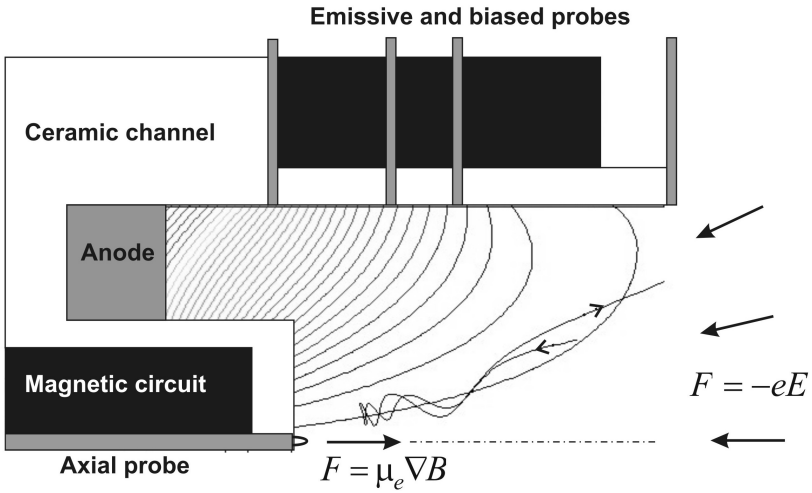
Issues:

- high plume divergence: damage to spacecraft components
- poor low-power and small-size scaling for microspacecraft applications
- scaling to high-power
- lifetime of hollow cathode
- high-freqency electromagnetic noise

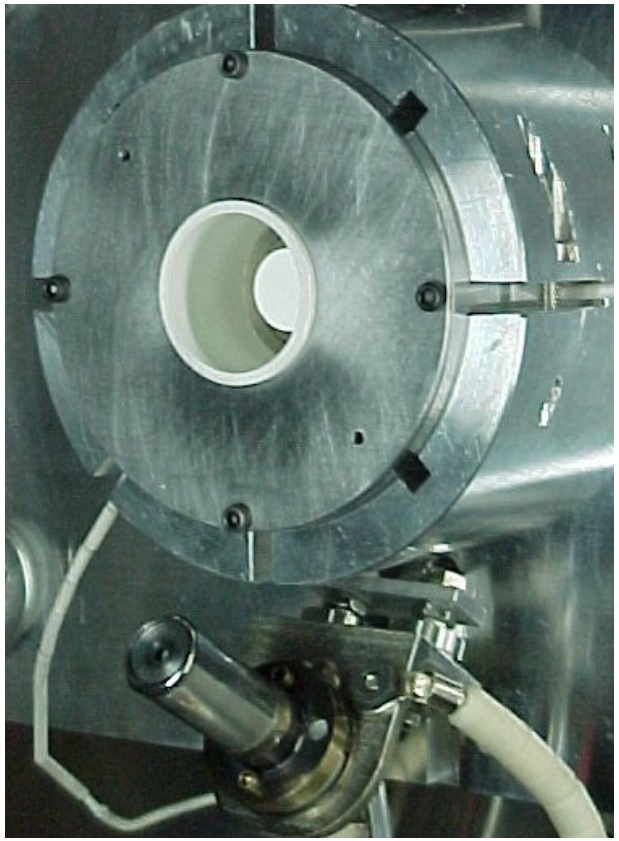
Basic Physics:

- Electron transport
- Plasma-wall interaction

Cylindrical Hall Thrusters

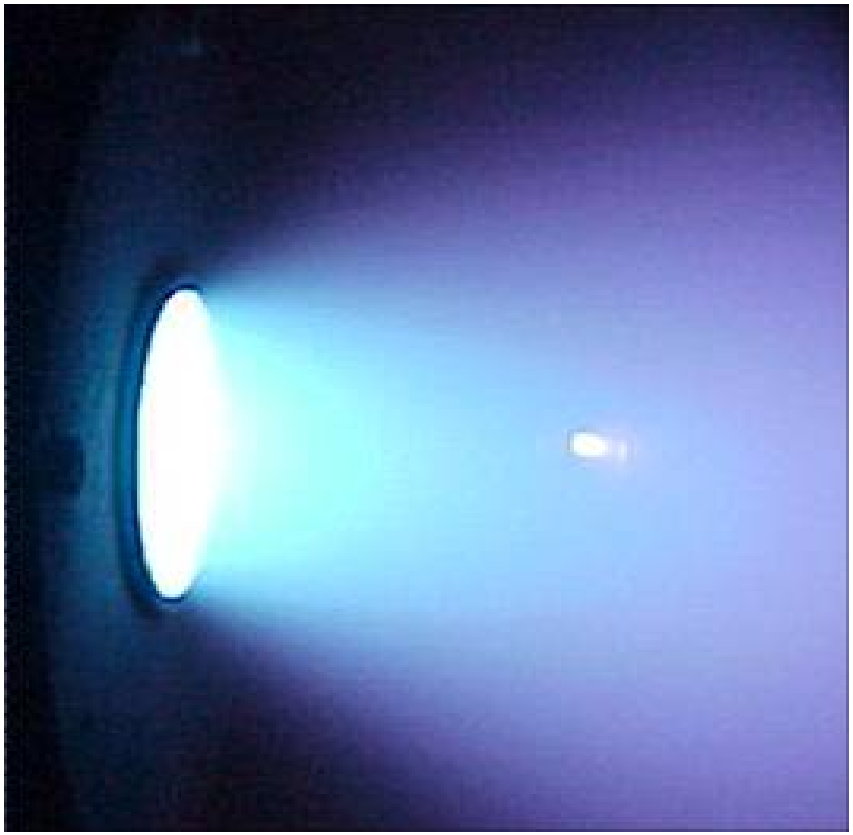


- magneto-electrostatic trap: axial electron confinement
- ionization in annular region; acceleration in cyl. region
- ions accelerated $\perp$ to **B**: away from walls, larger plume



3cm channel dia PPPL thruster

Cylindrical Hall Thruster in operation



3cm PPPL CHT

Performance:

- v_{ex}: 16–25 km/s
- thrust: 1–5mN
- power: 200–1000W
- divergence: 70°
- efficiency: 20–30%

Parameters:

- $B \sim$ 100–1400G, $T_e \sim$ 5–20eV, $T_i \sim$ 1eV,
- $n_e \sim 10^{11}$–$10^{12}\mathrm{cm}^{-3}$, $\lambda_e, \lambda_i >> L$

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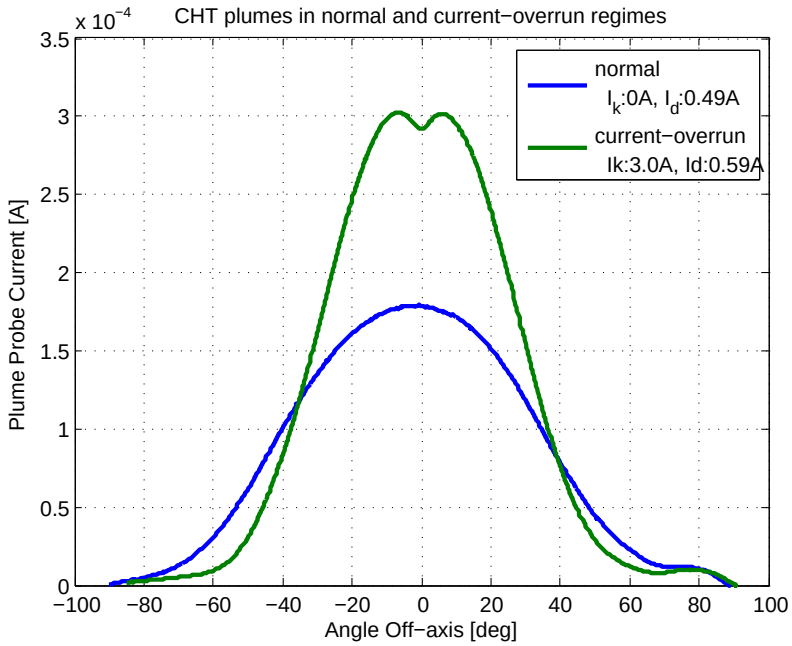
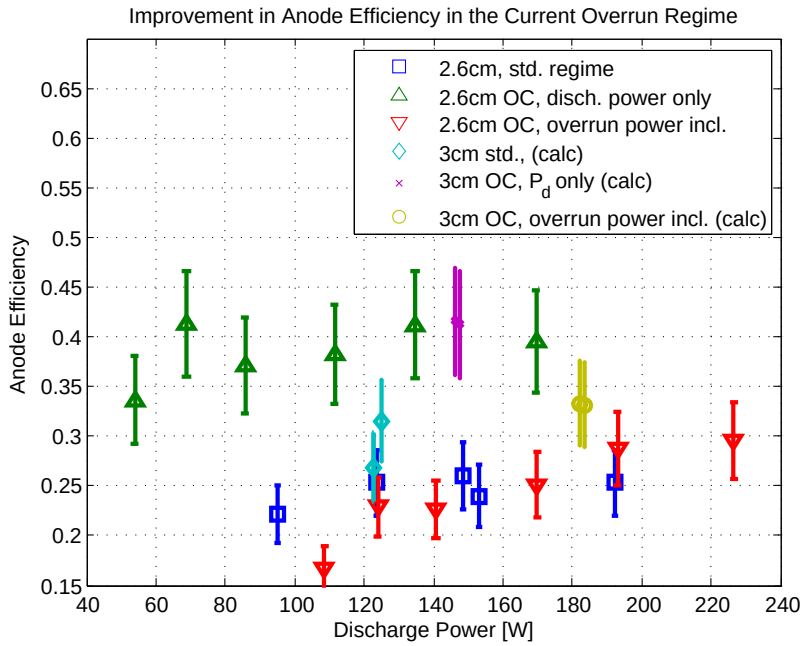
Motivation: Reduce Plume & Enhance Efficiency



Typical narrowing of the thruster plume in the direct (mirror **B** field) configuration current OC regime, using the 3cm CHT.

- generally assumed the discharge extracts all the electrons necessary for operation (neutralization and best performance): *self-sustained mode*
- previous work discovered plume-narrowing achieved by "overrunning" the discharge current (I_d): *non-self-sustainted mode*
- I_d increased by driving a cathode-keeper current or biasing segmented electrodes

Measured Thrust and Efficiency



Measured anode efficiency (η_A) of the 2.6cm CHT demonstrating the improved η_A of the OC regime. Also calculated η_A for the 3cm CHT derived from plume ion current and ion energy measurements.

- Anode efficiency (η_A) almost doubled; up to ~40%
- Thrust increased 50–100%; up to 6.5mN
- performance still enhanced using little overrun power
- direct thrust measurements consistent with measured ion current and ion energy in plume

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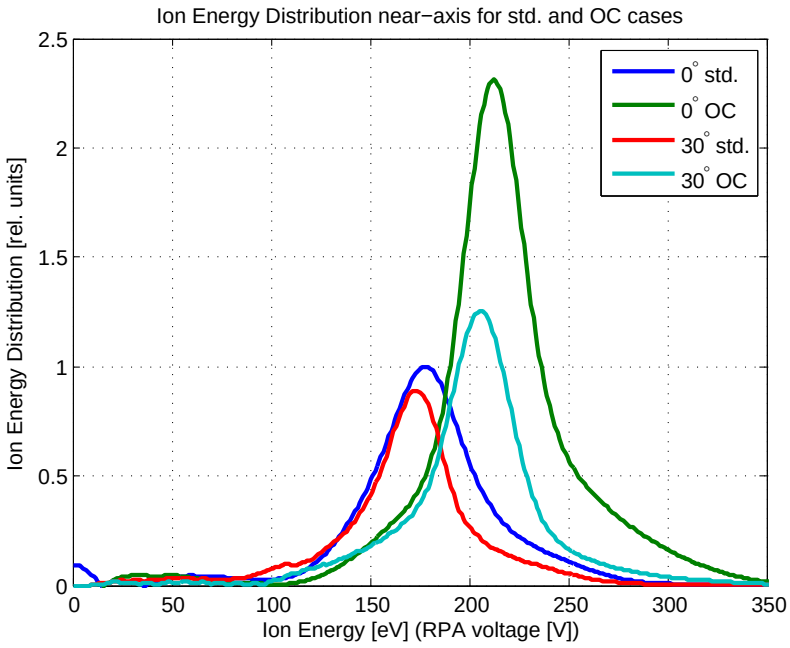
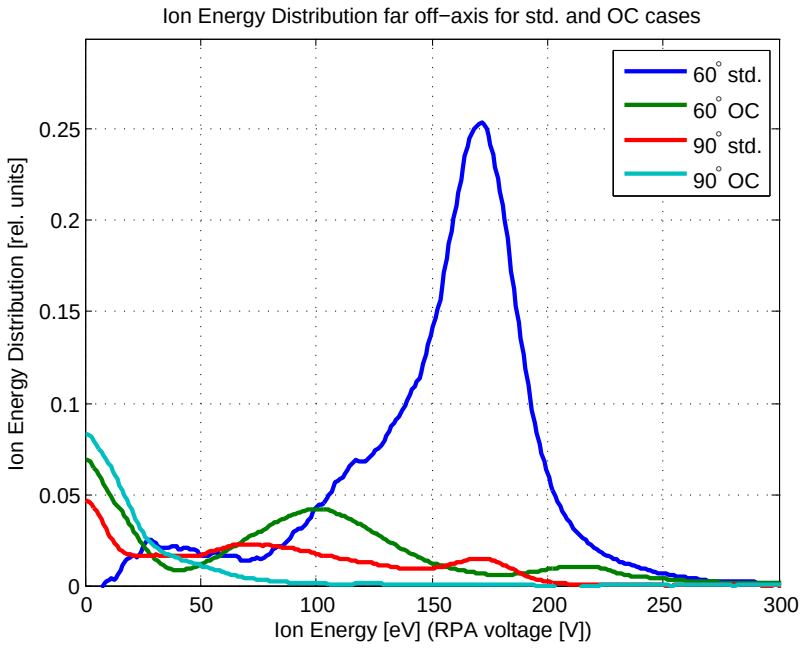
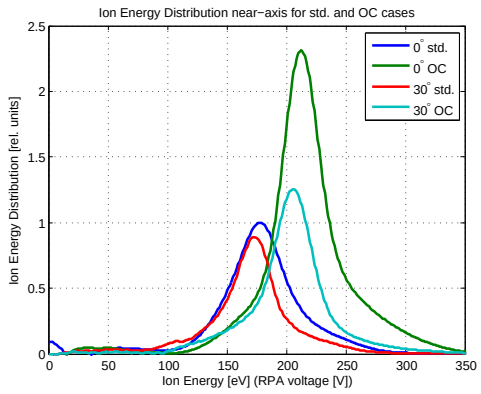
Ion Energy

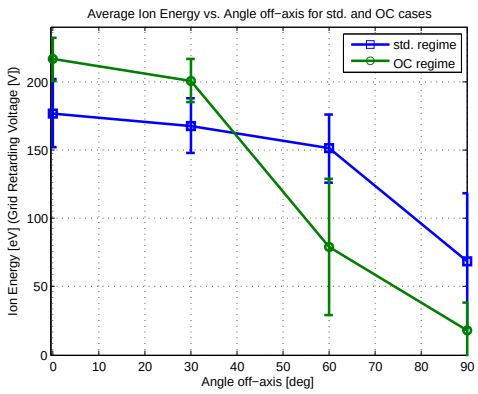
- on-axis ion energy is typically 10–20 eV higher in the current-overrun regime
- off-axis ion energy is substantially reduced





Ion Energy





Possible explanations for on-axis energy shift:

- Ambipolar potential changing thruster floating potential with respect to ground
- Shift in ionization region due to increased T_e or n_e
- Decrease in cathode-plume resistance

Ion Energy, contd.

- Ambipolar potential changing thruster floating potential with respect to ground
  - Langmuir probe measurements in the plume region indicate: $V_f \approx 0.5$V, $T_e \approx 0.4$eV, and $V_p \approx 2.6$eV
  - These parameters remain unchanged in the current-overrun regime.
- Shift in ionization region due to increased T_e or n_e
- Decrease in cathode-plume resistance
  - higher electron emission current in OC regime
  - for negative-resistance devices (ex. glow discharge), higher current results in lower potential drop
- Positive shift in the cathode potential sufficiently accounts for the increased ion energy on-axis for hollow cathode experiments using 0.4 mg/s Xenon flow rate.

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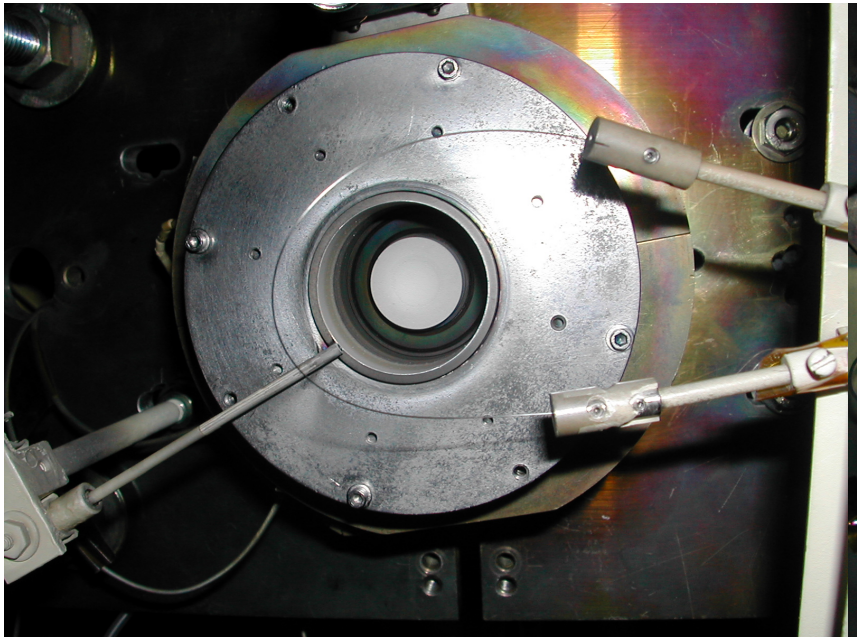
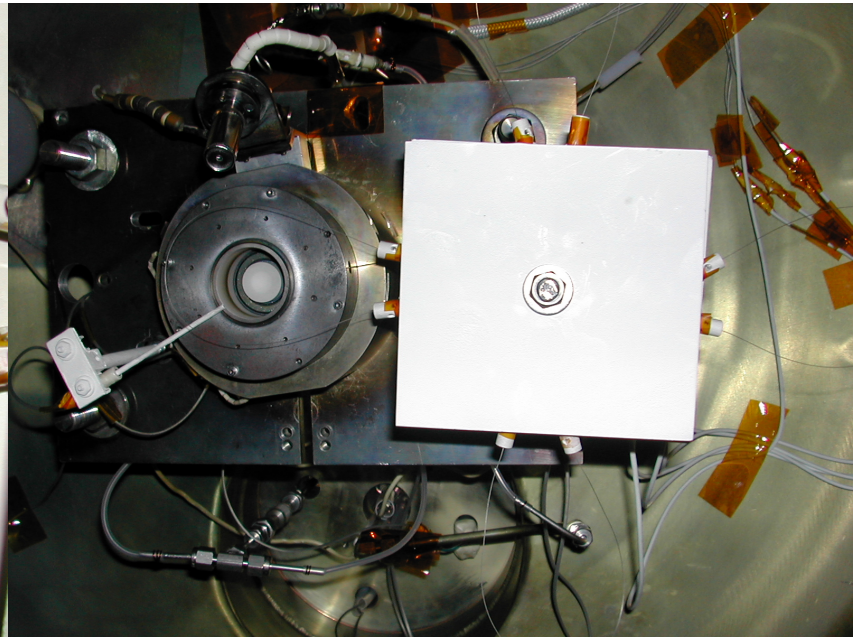
CHT operation with filament cathode

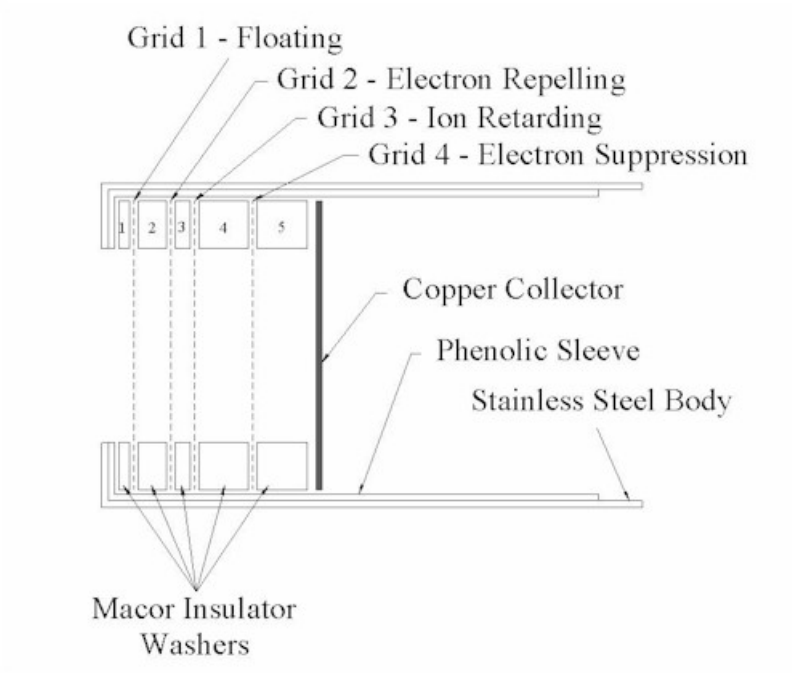
Motivation:

- Eliminate complex internal physics of the hollow cathode
- Direct control of electron emission source via heater current





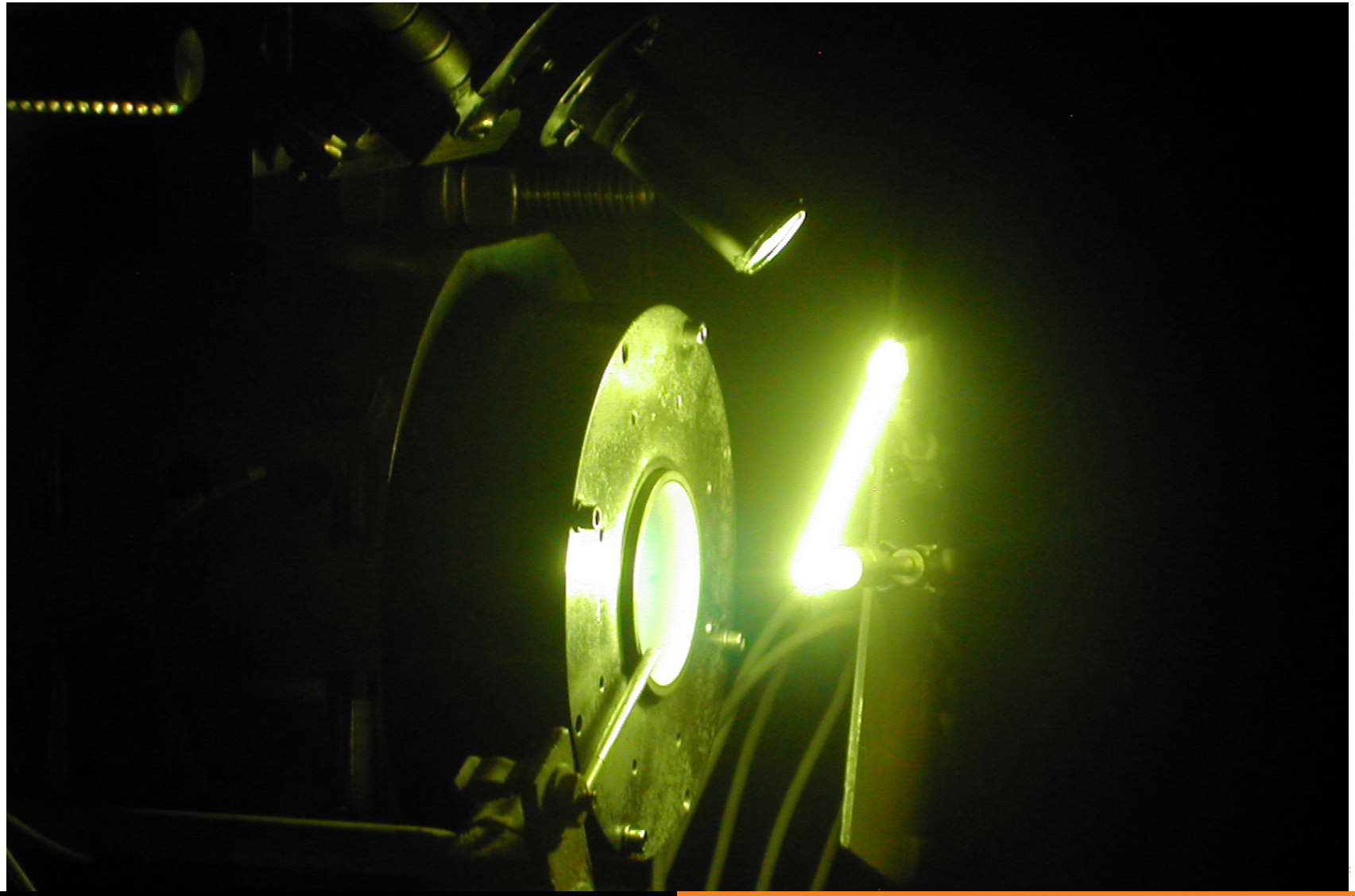
Diagnostics



http://www.engin.umich.edu/dept/aero/spacelab/diagnostics/RPA.htm

- biased graphite probe to measure plume I_{ion}
- 4-grid RPA to measure ion energy distribution
- Langmuir probe to measure V_f at channel exit
- digital scope to measure fluctuations in V_d, I_d, V_f

Operation



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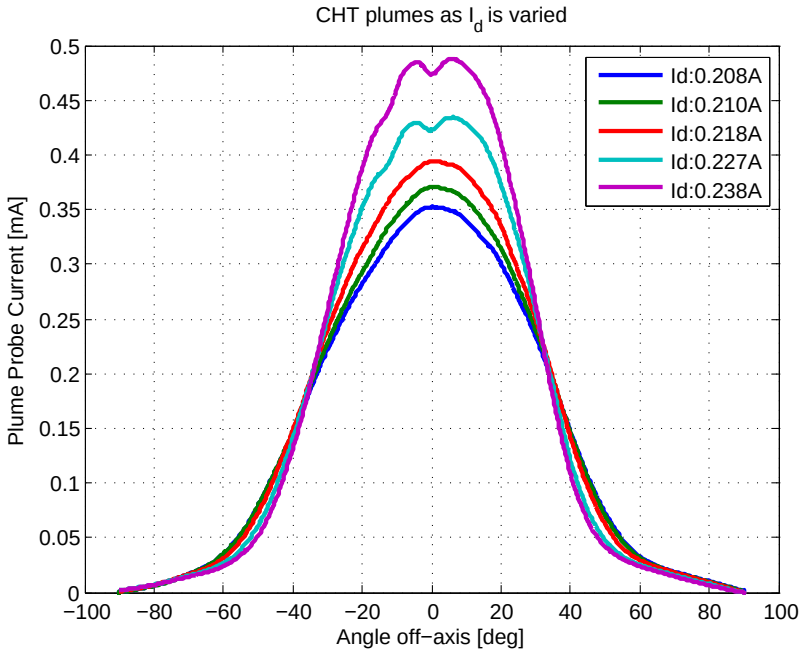
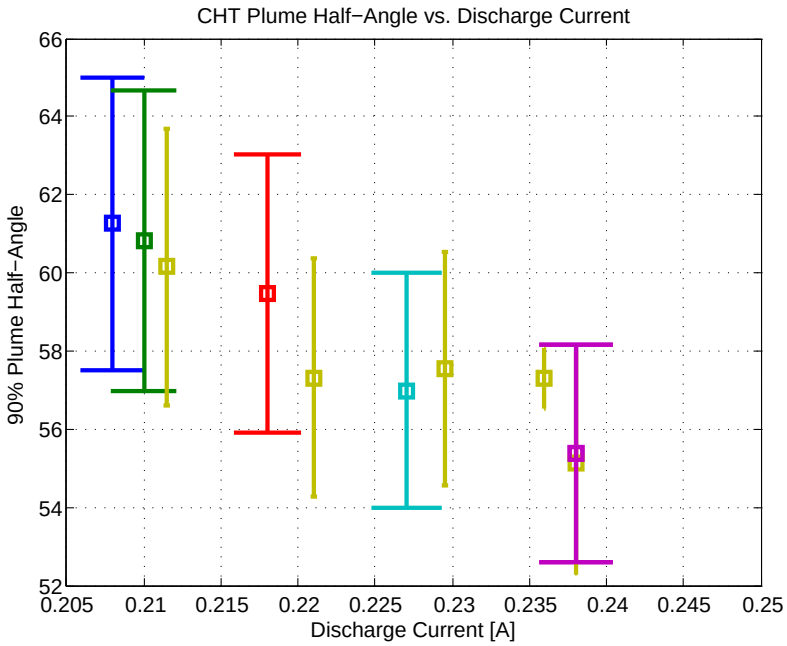
Plume strongly affected by source electron current

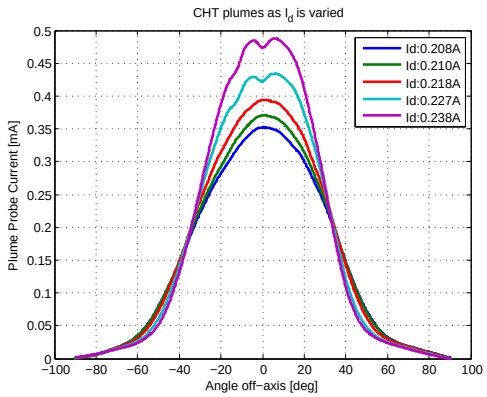
- plume-narrowing can be controlled by varrying the source electron emission
- internal physics of the hollow cathode is not relevant for understanding performance enhancement



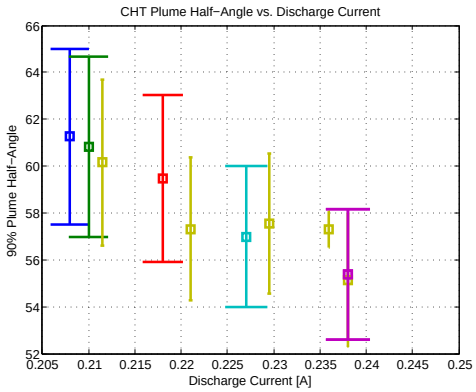


Effect of electron source

Ion current vs. angle off-axis



Plume 90% half-angle vs. I_d

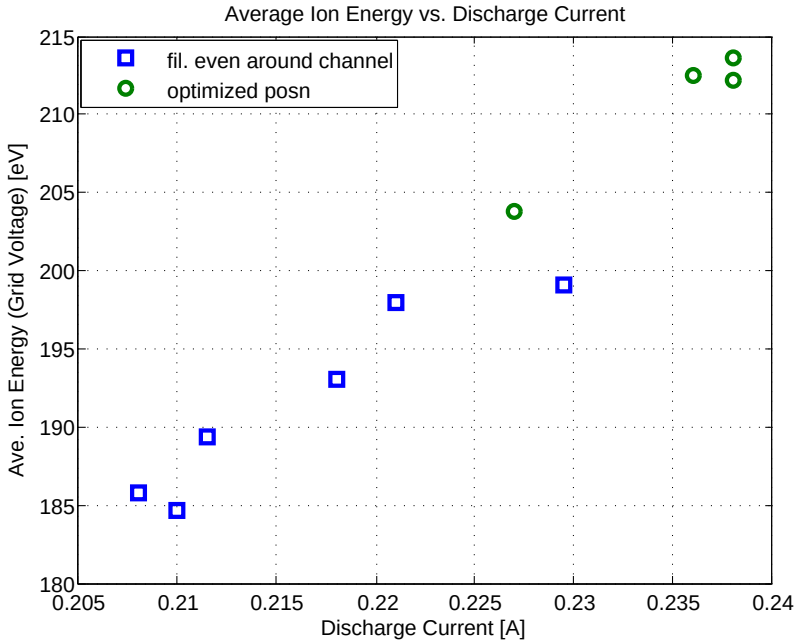


- Source electron emission is ($I_{emission}$) increased with heater current.
- Discharge current (I_d) increases with $I_{emission}$; plume angle decreases.
- I_d saturates to maximum; increase of $I_{emission}$ does not increase I_d or improve plume angle: I_d can be electron **source-limited** or **mobility-limited**
- saturated I_d depends on **position** of filament cathode

Position Dependence

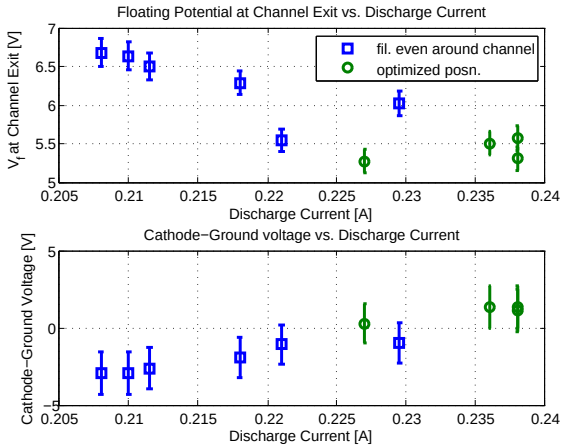
- **B** outside the channel is sufficiently strong to magnetize the electrons $\rho_e \leq 1$mm
- electrons are deposited on particular field lines
- moving the filament position radially or axially can affect I_d and cause a transition between regimes

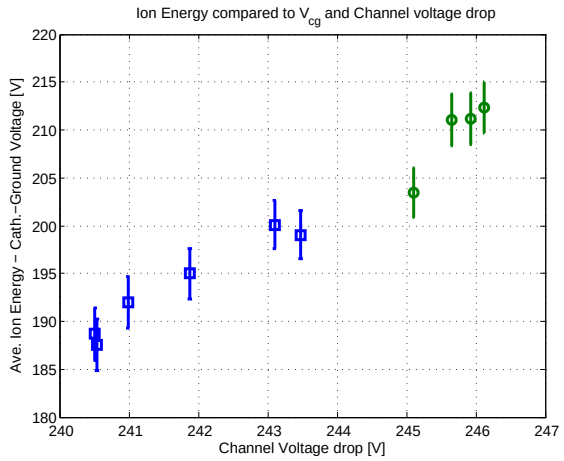
Ion energy increases with discharge current



- the ion energy distribution (IEDF) near-axis shifts to higher energy with increased I_d
- Ion energy does not increase with additional $I_{emission}$ once I_d is saturated (the mobility-limited regime)
- if the filament position is moved and I_d changes, E_i continues to increase with I_d

Ion energy increases with discharge current





- unlike experiments with the hollow cathode neutralizer, the IEDF shift is greater than the sum of increased channel voltage drop and cathode voltage
- using filament cathode with 0.2 mg/s Xenon flow rate through anode, energy shift can exceed 40 eV.
- indicates that ionization must be taking place in a region of higher V_{plasma}, ie. ionization region is shifted relative to equipotential surfaces

Conclusions

- Enhanced performance current-overrun regime is due to increased electron emission from the cathode
  - **source-limited** and **mobility-limited** regimes
  - in the source-limited regime, increasing electron emission from the cathode improves performance
  - plume angle is reduced as I_d increases until saturation: the mobility-limited regime.
- IEDF (near-axis) shifts 10–40 eV as I_d increases to saturation
  - using a hollow cathode, shift in cathode potential is sufficient to explain the energy increase
  - using a filament cathode, the ionization region must shift relative to equipotential surfaces
- Discharge operating parameters are **sensitive to the position of electron emission**

Future Direction

- Develop theory for the source-limited regime. Do instabilities contribute to increased cross-field transport?
- Characterize fluctuations to determine if cross-field transport changes from one regime to another.
- Confirm presence of multicharged Xenon (Martin's job!)
- Measure changes in n_e, T_e with Langmuir probes mounted on the channel wall or a fast reciprocating probe inside the channel
- Develop theory for electron confinement in the thruster channel. Apply anomalous transport models based on the fluctuation spectrum to better understand electron cross-field transport. Can this explain I_d saturation?
- Numerical simulations to understand how equipotential surfaces (hence ion acceleration) are modified inside the thruster channel as discharge current is varied. Can this explain plume enhancement?

Acknowledgments

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Talk available at `http://princeton.edu/~erikg/`